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New siren tones optimised for increased detectability distances of emergency vehicles

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Sirens from emergency vehicles are particularly annoying for people living in the vicinities of emergency centres. In order to reduce their discomfort, the present work computes the optimal output power and frequency content of the sirens by taking into account the car noise reduction, the background noise inside the car and the hearing threshold. The combination of these parameters gives rise to frequency windows where the sirens are more effective, hence new siren tones are proposed and their annoyance is assessed through a jury test procedure. The new tones can either increase the detectability distance by 40% without increasing their annoyance or reduce their sound pressure level by 3 dB while keeping their effectiveness in being detected.

1. Introduction

Acoustic sirens from emergency vehicles are an annoying part of the soundscape in cities, especially those from fire brigades and ambulances since they tend to be clustered around fire departments and hospitals bothering the same population on a regular basis. For example, in Barcelona, the Medical Emergency Service makes 400 services per day using the siren.

Although there exist local regulations about the minimum and maximum power for sirens it is not well known whether these levels are adequate.

The power regulations vary for different countries, not only in terms of sound pressure level (SPL) but also at what distance has to be measured. Propagating these different SPL at a distance of 3 m, the European Directive 70/388/EC [1] requires a minimum of 101.5 dBA, France requires a minimum of 106.5 dBA for the police and the fire brigades and between 86.5 dBA (night levels) and 106.5 dBA for ambulances [2], while the range is between 111.5 dBA and 121.5 dBA in Italy [3]. In Spain, the day levels are not regulated and the Real Decreto 1367/2007 [4] only regulates the night levels that must be between 70 dBA and 90 dBA. Still, in Barcelona the city regulations [5] require a level at night between 78 dBA and 98 dBA and a maximum of 103 dBA during the day. On the other hand, SAE International (Society of Automotive Engineers) recommends a minimum of 118 dBA [6]. In general, the power requirements are somewhat arbitrary and have wide intervals.

As for the frequency content of sirens, it does not exist any regulation at all. Although the wail and yelp standard tones (scans from 600 Hz to 1200 Hz at 12 cycles/min and 180 cycles/min respectively) are widespread, the two-tones siren is not as well standardized and different countries use different frequencies and different cycles/min. Even inside the same country different frequencies are used to discriminate the type of service. In France, for example, the police uses a 435–580 Hz at 55 cycles/min, the Gendarmerie 435–735 Hz at 55 cycles/min, the firefighters 435–488 Hz at 27 cycles/min and the ambulances 435–651 Hz at 55 cycles/min. In particular, in Barcelona, the local police uses a two-tones with 550 Hz and 750 Hz at 68 cycles/min, and the ambulances have a three-tones with the sequence 420 Hz – 516 Hz – 420 Hz followed by a pause at 60 cycles/min.

Related to the frequency content of sirens, there are studies that propose the use of broadband sirens [7,8] to avoid the localisation issues [9] of pure tone sirens.

Other studies quantify the subjective perception of danger, unpleasantness or urgency introducing different warning sounds playing with the length, period, pauses and frequencies of the signal [10–14].

A recent review on the subject can be found in [15].

The objective of this study is to define new tones for sirens and their required output power to produce less annoyance while keeping the detectability distances of the current tones. Only variations of the classic tones (wail, yelp and two-tones) have been investigated because these tones have the advantage of recognition, which favours detectability [8].

The article is structured as follows: in the following section it is described the procedure used to compute the optimum power and

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frequencies for sirens, afterwards the results are presented and discussed, and finally the proposed new tones are evaluated by means of a jury test before reaching the conclusions.

2. Methodology

The problem of the detection of a siren by a driver is equivalent to the problem of detecting a pure tone (the siren) masked by broadband noise (the background noise level inside the receiver car, $L_p^{background}$). The presence of the background noise reduces the ability of the ear to discern other sounds. Thus, the hearing threshold is elevated because of the masking noise. The masked hearing threshold (MHT) is the hearing threshold in quiet (HT) plus the elevation of the hearing threshold due to the broadband noise [16]:

$$MHT = HT + L_p^{background} + 10\log_{10}\frac{f_0\pi^2}{Q(f_H - f_L)} \tag{1}$$

where Q is the figure of merit for the ear considered as a filter (as tabulated in [16]), f_0 is the central frequency of the 1/3 octave band and $f_H - f_L$ is its bandwidth.

However, a sinusoidal signal with SPL equal to the masked hearing threshold would be detected only with a response rate of 50% [17]. Since the siren must be clearly audible, its SPL inside the car must be well above the masked hearing threshold. Several studies indicate that for a signal to be clearly detected its level must be 12–15 dB above the hearing threshold [18–20].

It can be argued that the listener's attention to driving may impair its ability to detect the siren. In this regard, Wilkins [18] showed that performing a foreground task may affect the detection of a background siren with a SPL below the hearing threshold but it does not affect the detection of a siren with a SPL over the hearing threshold.

In order to grant detection, several detectability criteria have been applied in the present study. In particular, [19] suggests that to be reliably audible a warning must have at least four frequency components 15 dB above the masked hearing threshold. On the other hand, [21] suggests that the siren will be clearly detected if, inside the receiver car, there is one tone 15 dB above the masked hearing threshold and two or three more tones, in different 1/3 octave bands, 10 dB above the masked hearing threshold. Later, [20] uses one tone 15 dB above the masked hearing threshold and two more tones 10 dB above it to investigate on the detectability of train horns. The four detectability criteria followed in the present study, from more to less demanding, are:

- C1: Four tones in different 1/3 octave bands 15 dB above the masked hearing threshold.
- C2: Three tones in different 1/3 octave bands 15 dB above the masked hearing threshold.
- C3: One tone 15 dB above the masked hearing threshold and three more tones, in different 1/3 octave bands, 10 dB above the masked hearing threshold.
- C4: One tone 15 dB above the masked hearing threshold and two more tones, in different 1/3 octave bands, 10 dB above the masked hearing threshold.

So that C3 and C4 are relaxed versions of C1 and C2 respectively.

At the position of the car, but outside it, the required SPL of the siren is obtained from the previous criteria plus the car noise reduction.

On one side there is the required SPL at the receiver car position for the siren to be detected, and on the other side there is the distance at which the siren must be in order to meet this requirement, i.e. the distance of detectability. Knowing the SPL of a siren at a given frequency and at a fixed distance r_0, $L_p(r_0)$, the distance of detectability for that frequency, r, is computed with the propagation (as a point source) of the required level from the receiver vehicle, $L_p(r)$, with the equation:

$$L_p(r) = L_p(r_0) + 20\log_{10}\left(\frac{r_0}{r}\right) \tag{2}$$

There are two spectra to be compared, one is the masked hearing threshold, calculated from the car's interior background noise, the elevation of the hearing threshold and the hearing threshold in quiet (Eq. (1)). The other one is the siren spectrum, propagated to a distance r, with Eq. (2), minus the car noise reduction. The first one is calculated in 1/3 octave bands, and the second one is calculated in 1/24 octave bands. That is, a pure tone (narrow band and measured in 1/24 octave bands) masked by a broadband noise (measured in 1/3 octave bands).

So in order to define the proper acoustic power for a siren to be heard from inside a car it is necessary to measure the car noise reduction, its interior background noise, the hearing threshold and the siren spectrum. All these variables will be presented and measured in the following sections.

Noise reduction and interior background noise have been measured for ten different cars of different categories, motors and ages: Alfa Romeo GT (2005), Audi A4 (2008), Chrysler Voyager (1996), Citroen C2 (2008), Fiat Punto (1999), Ford Cmax (2007), Ford Fiesta (2004), Ford Focus (1999), Opel Astra (2005) and Seat Ibiza (1997).

2.1. Car noise reduction

The noise reduction measurements have been based on the *in situ* procedure of the norm ISO 11957 [22].

The measurements took place in a closed track, far from reflecting surfaces (other than the soil) and with low background noise. Inside each car, a dummy at the driver's position wore three microphones attached to its head. Outside the car, a microphone was situated in the car's ceiling just over the dummy's head. Three loudspeakers were situated at 5 m of the front of the car, the front passenger's side and the back of the car in order to measure the car noise reduction for sounds coming from different sides of the car. The loudspeakers emitted pink noise at such power as to ensure that the interior SPL be of at least 12 dB over the background level for each 1/3 octave band. The noise reduction, *NR*, is the difference between the SPL outside and inside the car:

$$NR = L_{p_{ext}} - L_{p_{int}} \tag{3}$$

Fig. 1 shows the noise reduction in 1/24 and 1/3 octave bands from 100 Hz to 10,000 Hz for each of the ten cars measured for a source coming from behind. The noise reductions are measured in 1/24 octave bands, the same as the siren spectra in order to make the proper substractions.

When measured in 1/3 octave bands, the car noise reductions have a common trend for all the ten cars. The noise reductions show three dips: one between 200 Hz and 500 Hz, another between 1000 Hz and 1250 Hz and a third one around 4000 Hz. These represent three windows of opportunity for the siren tones. As a consequence, one of the new proposed tones for the siren will be a two-tones combining the 400 Hz and the 1000 Hz frequencies. The 4000 Hz window is not convenient to use because of the higher air and asphalt absorption at high frequencies [23] and the increase of the hearing threshold at high frequencies with age. Besides, the new tones which contained the frequency of 4000 Hz were considered particularly annoying in a jury test. After inspection of the results from the noise reduction tests, two new scan tones are proposed which benefit from the low frequency window by extending the wail and yelp scan tones down to 315 Hz.

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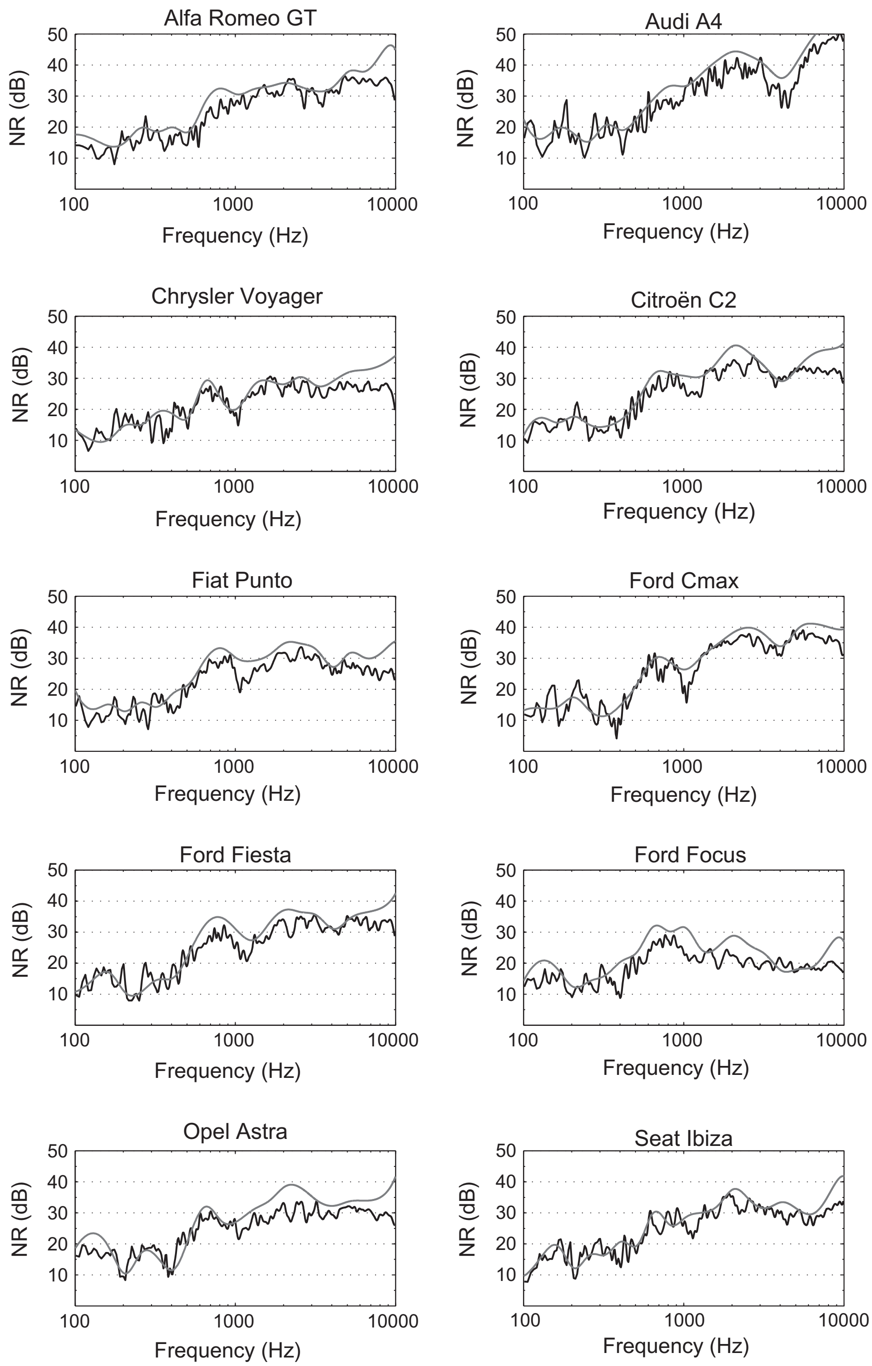

Fig. 1. Car noise reductions in 1/24 (black line) and 1/3 (grey line) octave bands for a sound source directed at the rear windows of the vehicle.

2.2. Interior background noise

The car noise reduction decreases the SPL inside the vehicle. In addition, the noise level inside the receiver car raises the driver's hearing threshold in quiet because it masks the siren noise.

The noise level inside each vehicle was determined with a sound level metre situated at the front passenger's head measuring the SPL in 1/3 octave bands every 125 ms during a ten minutes urban drive without speaking and with the radio off. The background noise used to calculate the elevated threshold of hearing is the arithmetic average for these ten minutes, since the key parameter is not the equivalent SPL for ten minutes but the average instantaneous SPL.

The ten minute urban drive took place during weekdays from 5 pm to 6 pm in busy traffic conditions through a mix of one-way and two-way streets, from one to three lanes, in the centre of the city of Terrassa with traffic lights in most of the cross-roads. The maximum speed reached was 50 km/h but most of the drive was made in continuous starts and stops, accelerations and decelerations, typical of an urban drive.

Fig. 2 shows 1/3 octave band spectra of the interior background noise for the ten cars measured. The typical spectrum is dominated by low frequencies, it falls down about 10 dB from 100 Hz to 400 Hz, then it reaches a plateau up to a 1000 Hz and rapidly falls down again at higher frequencies.

2.3. Hearing threshold

The hearing threshold in quiet, Fig. 3, has been obtained from ISO 389-7 [17], which specifies the reference hearing threshold

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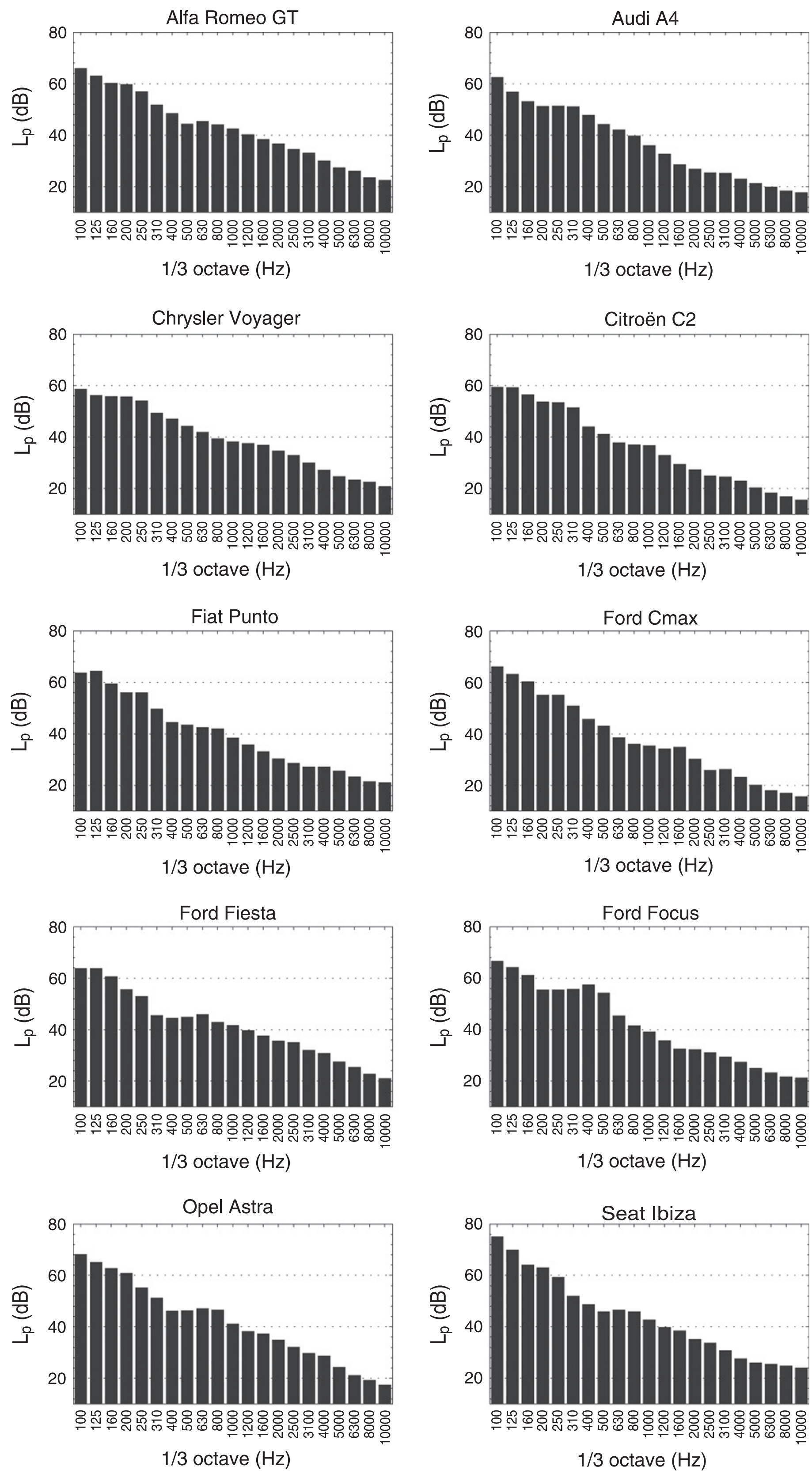

Fig. 2. Interior background noise in 1/3 octave bands for each car in urban driving regime.

as the average for an 18 years old otologically normal population, and ISO 7029 [24] which gives the increment in the hearing threshold as a function of age and gender.

Since males have higher hearing thresholds than females, they represent more restrictive conditions for the siren to be heard. Fig. 3 gives the average hearing threshold for 20, 40 and 60 years

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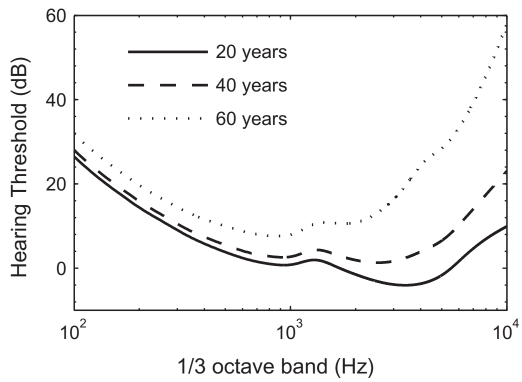

Fig. 3. Hearing threshold in quiet as a function of age.

old males. The choice of an age for the hearing threshold has a big impact on the detectability distance of a siren. That is, the lower the hearing threshold (the lower the age of the population considered), the larger the detectability distance.

Also, the hearing threshold of a given percentage of the population of a certain age can be computed with ISO 7029 [24] that gives the statistical distribution of hearing thresholds around average values. As an example, in order to include 95% of the 40 years old male population the hearing threshold would be around that of the average 60 years old male.

Since sirens should be heard from a fair distance by any driver, in order to compute the detectability distance of a siren, the hearing threshold that includes the 95% of the population with normal hearing should be used. Unfortunately, under these conditions, the detectability distance of any siren goes below 12 m (see Table 4).

2.4. Siren spectra

The siren SPL are measured at a distance of 1 m with both the loudspeaker and the microphone at zero height on a hard ground in a semianechoic room. This makes the SPL to be 6 dB over that measured in conditions of free field, but avoids the fact that the level at some frequencies can be either amplified or decreased by the interferences of the direct wave and reflected wave in the ground of the semianechoic room [25]. The SPL measured in this condition for each siren tone is decreased in 6 dB in order to obtain the SPL at 1 m of a point source in free field and to be able to propagate it as such.

The propagation law adopted for the sound of the siren is that of a point source in free field. There are several reasons to choose this rather simple propagation law. First, there is no need to introduce atmospheric corrections due to the short distances involved [26] (mostly under 100 m and always under 200 m). Second, there is no need to introduce the effects of the directivity of the source since it is only necessary to know the propagation in the circulation direction.

The use of a propagation model of a source near the ground has also been rejected due to the variety of situations in which the emergency vehicle and the receiver vehicle may be involved. First, there are several different siren heights (e.g. under the hood ~0.4 m, motorbike ~1 m, car ~1.5 m, ambulances >2 m, firefighters >2.5 m). Second, the distance from the emergency vehicle to the building facades depend on the type of street (e.g. from 3 m for a single lane street to more than 10 m for wide avenues). Then, all the reflections are attenuated by different obstacles, like other cars, in different configurations.

Finally, for the case of the scan tones, wail and yelp, the direct and the reflected wave are not of the same frequency, due to the time lag between them, which may prevent interferences. And, in any case, for the two-tones, the interferences between the direct and the reflected wave scan all the range of frequencies as the emergency vehicle approaches the receiver car.

For all these reasons the propagation of a point source in free field has been used as a standard to compare the detection distances for the siren tones.

2.5. Detectability distances

In order to compare the performance of different sirens it is convenient to define the distance of detectability as the maximum distance at which a siren can be detected inside a car, given each detectability criterion adopted in this study. The distance of detectability depends on the car noise reduction, its interior background noise, the hearing threshold and the siren spectrum. All these parameters have been previously presented.

The detectability distance can be calculated for each 1/24 octave band of a siren spectrum solving r in the following equation:

$$\Delta + HT + L_p^{background} + 10\log_{10}\frac{f_0\pi^2}{Q(f_H - f_L)} = L_p(r_0) + 20\log_{10}\left(\frac{r_0}{r}\right) - NR \qquad (4)$$

where Δ is the raise in the masked hearing threshold to grant detection (e.g. Δ = 15 dB for C1 and C2).

The maximum distance at which each detectability criterion is met is the distance of detectability. For instance, for the detectability criterion C4, the detectability distance is the maximum distance at which the SPL of a tone of the siren inside the receiver car is 15 dB above the masked hearing threshold (Δ = 15 dB) and two more tones, in different 1/3 octave bands, are 10 dB above the masked hearing threshold (Δ = 10 dB).

2.6. Optimum siren tone

The best possible two-tones siren is searched with an algorithm that minimises the SPL of the siren with the condition that it is clearly detectable from 60 m by a 60 year old male with average hearing threshold inside each of the 10 cars measured in this study given the detectability criterion C3.

The required distance of detectability is the brake distance plus the distance travelled by the emergency vehicle during the reaction time of its driver and the time it takes the receiver vehicle to get away of the trajectory of the emergency vehicle. So it is not the distance required to avoid collision, but the distance required to avoid interfering with the normal trajectory of the emergency vehicle. The brake distance, $v^2/2g\mu$, is obtained from the work-energy principle. In the case of an emergency vehicle going at 50 km/h and a receiver vehicle at full stop, considering a conservative friction coefficient between the tire and the asphalt, μ = 0.6, in order to cover low grip circumstances (μ = 0.7–1 depending on the source [27–29]), a reaction time of 1.5 s, and 1.6 s to move the car away from the trajectory of the emergency vehicle (to move 5 m at an acceleration of 3.7 m/s^2; obtained from a car that can go from 0 to 20 km/h in 1.5 s), the detection distance needed is 60 m.

The minimisation algorithm only considers tones in the 1/3 octave bands centred between 200 Hz and 2500 Hz. Higher frequencies can lead to more annoying tones (as it will be shown by the jury test) and are also less adequate for people with hearing thresholds above the average.

The minimisation method applied is the simplex method [30]. Due to the impossibility of finding the global minimum, the minimisation is computed 3000 times with a random initial siren spectrum and the global minimum is considered as the spectrum with minimum global SPL among the 3000 solutions. After that many minimisations (an hour of computing time in an Intel Core 2 Duo

@ 2.4 GHz), the global SPL of each minimisation very rarely decreases the minimum already found, and if it does it is by less than 0.1 dB and with a very similar result spectrum.

The condition for being detected from 60 m is adopted only for the standardisation of the minimisation. The spectrum obtained from this minimisation is the best tone possible for the siren to be heard at any distance (following the propagation of a point source in free field). However, the detectability distance of this tone can be affected by increasing or decreasing the SPL of the siren.

The two-tones is created with two fundamental frequencies plus two harmonics for each fundamental frequency. The harmonics are supposed to have the same SPL as the fundamental frequency. This represents a very high total harmonic distortion (THD), with an attenuation level of 0 dB for the first two harmonics. However, measurements of typical two-tones show that sirens can have such a high THD. For example, the spectrum of the Standard Two-Tones in Fig. 4 shows the fundamental tone at 550 Hz with a level of 95 dB, while the first two harmonics have levels of 109 dB, and the second fundamental tone at 750 Hz has a level of 101 dB for 115 dB and 109 dB its two first harmonics. This is because of the non-linear nature of the electromechanical transducer, the high input power and the high efficiency of the loudspeaker around 1 kHz.

3. Results

The best two-tone siren obtained from the minimisation algorithm has the fundamental frequencies at 360 Hz and 590 Hz. In addition, in order to take advantage of the frequency windows observed in the car noise reduction 1/3 octave band spectra, new tones have been proposed by extending the scans wail and yelp down to 315 Hz and also a new two-tones with frequencies of 400 Hz and 1000 Hz. The list of tones evaluated can be seen in Table 1 and its corresponding spectrum is plotted in Fig. 4. The spectra of the Standard Two-tones slow and fast is the same, so the former is not shown. The wail and yelp scans with the same intervals have also the same spectra as it can be seen.

All these tones have been reproduced with sirens from Federal Signal VAMA, in particular by an AL252N loudspeaker coupled to an amplifier AS320 for the scan tones and to a GEP500 for the two-tones. This electro-mechanical system introduces some noise as well as harmonics to the output signal (Fig. 4) which ends up being different than the input signal. So for example, the input signal of the Optimised Two-tones is the fundamental tones at 360 Hz and 590 Hz of the synthetic spectrum coming from the minimisation algorithm and zero emission elsewhere, but the reproduced signal gives not only harmonics but also a broadband non-zero noise.

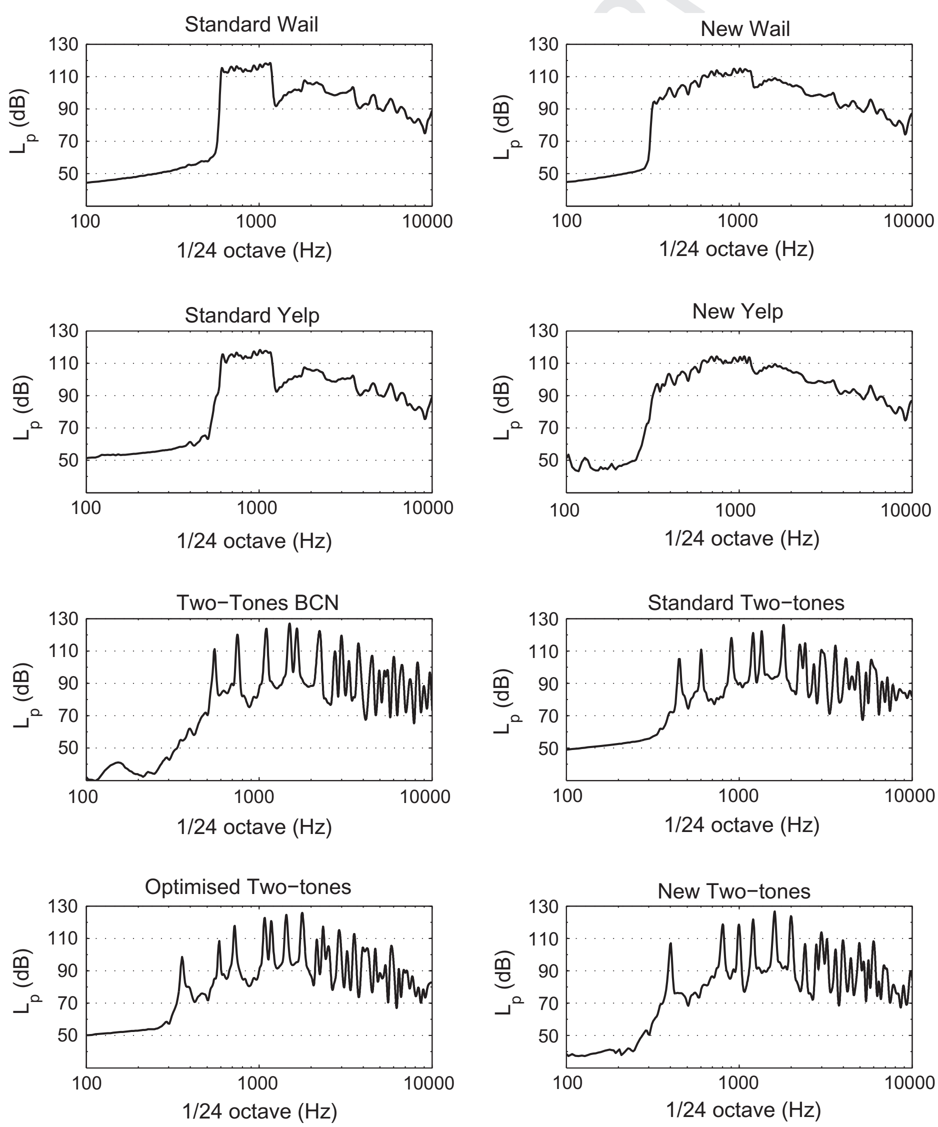

Fig. 4. 1/24 octave band spectra measured at 1 m for each siren tone.

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Table 1
List of the siren tones evaluated.

#	Tone	Description
1	Standard Wail	600–1200 Hz @ 12 cycles/min
2	New Wail	315–1200 Hz @ 12 cycles/min
3	Standard Yelp	600–1200 Hz @ 180 cycles/min
4	New Yelp	315–1200 Hz @ 180 cycles/min
5	Two-tones BCN	550 Hz and 750 Hz @ 68 cycles/min
6	Standard Two-tones slow	450 Hz and 600 Hz @ 33 cycles/min
7	Standard Two-tones fast	450 Hz and 600 Hz @ 68 cycles/min
8	Optimised Two-tones	360 Hz and 590 Hz @ 68 cycles/min
9	New Two-tones	400 Hz and 1000 Hz @ 68 cycles/min

Table 2
Detection distances for the scan tones averaged for the 10 cars measured. Detection distances are given for a 40 and 60 year old male with average hearing threshold and for each detectability criteria defined in Section 2.

Age (yr)	Criterion	Standard Wail distance (m)	New Wail distance (m)	Standard Yelp distance (m)	New Yelp distance (m)
40	C1	34	36	34	38
40	C2	46	48	46	51
40	C3	59	63	58	67
40	C4	76	80	75	85
60	C1	15	15	16	17
60	C2	22	24	22	25
60	C3	26	27	29	30
60	C4	38	39	38	41

Tables 2 and 3 show the detection distances, averaged for the ten cars measured, for a 40 and 60 year old male with average hearing threshold and for the scan tones and the two-tones respectively.

In order to properly compare the detectability distance for each siren tone, the global SPL of each tone has been normalised to the global SPL of the Standard Two-tones (123 dB at 1 m).

The New Wail and Yelp tones only slightly improve the results of the standard scans.

On the other hand, among the two-tones sirens the New Two-tones and the Optimised Two-tones improve the performance of the Standard Two-tones and the Two-tones of the Barcelona Police. In particular the Optimised Two-tones is the best tone, and only with the more relaxed detectability criterion C4, the performance of the Two-tones of the Barcelona Police comes close to it.

The Optimised Two-tones improve the detectability distances of the Standard Two-tones for each detectability criterion from C1 to C4 in 53%, 39%, 41% and 12%, respectively, with the 40 year old male average hearing threshold, and in 75%, 46%, 74% and 19%, respectively, with the 60 year old male average hearing threshold. These increments in the detectability distance can be also translated into decreases of the global SPL. So the SPL of the Optimised Two-tones can be decreased in 1 dB to 5 dB while keeping the same detectability distance as the Standard Two-tones. With a decrease in the global SPL of 3 dB, the Optimised Two-tones would have the same detectability distance as the Standard Two-tones for the detectability criteria C1, C2 and C3 for both hearing thresholds, 40 years and 60 years old.

3.1. Special cases

The calculations of the detectability distance in the previous section do not account for the increase of interior background noise due to the radio or motorway circulation nor the use of a hearing threshold that includes 95% of the population of age 60. In this section it is studied the decrease in the distance of detectability for these special cases.

Table 3
Detection distances for the two tones averaged for the 10 cars measured. Detection distances are given for a 40 and 60 year old male with average hearing threshold and for each detectability criteria defined in Section 2.

Age (yr)	Criterion	Two-tones BCN distance (m)	Standard Two-tones distance (m)	New Two-tones distance (m)	Optimised Two-tones distance (m)
40	C1	61	57	79	87
40	C2	96	88	109	122
40	C3	108	101	136	142
40	C4	166	155	168	173
60	C1	28	20	27	35
60	C2	43	37	41	54
60	C3	50	35	47	61
60	C4	75	63	64	75

The circulation around Barcelona's ring road has been studied with the Ford Cmax model. The interior background noise has been measured with a sound level metre situated at the head of the front passenger and driving at about 80 km/h (maximum allowed speed in Barcelona's ring road) over 10 min. The interior background noise increases from an $L_p = 69$ dB inside the city to an $L_p = 78$ dB in the ring road.

The effect of the radio has been studied also with the Ford Cmax model. The interior background noise has been measured with a sound level metre situated at the head of the front passenger and driving in normal circulation regime inside cities. The interior background noise with the music at two different volumes increase to $L_p = 77$ dB, for a volume subjectively comfortable, and to $L_p = 83$ dB for a volume subjectively high.

Table 4 shows the detectability distances for these special cases for the detectability criteria C1 and C4. The cases of the ring road and the music on have been computed with the average hearing threshold of a 40 year old male. The Ford Cmax model offered detectability distances around the average values for the case and sirens studied in the previous section so it was not a car with a particularly low or high detectability distances.

When using the hearing threshold that includes 95% of the population of age 60 or the interior background noise with the radio on and the music at a high volume the detectability distances are specially low.

These special cases show that for a siren to be detected under any circumstances and by any driver it requires an unreasonably high output power. For example, increasing the SPL of the sirens presented here to the SPL required by the SAE (a 4 dB increase) would increase almost by 60% the detectability distances, but, for the special cases presented in this section, the siren would still not be clearly detectable from a distance of 60 m. Moreover, lowering the power output of a siren means that it will be detected by less drivers. As a conclusion a reduction of annoyance by a

Table 4
Detectability distances in metres for the special cases of circulation in ring roads, circulation with the radio on at two different volumes and a hearing threshold that includes 95% of the population of age 60. Detectability distances are given for the detectability criteria C1 and C4 defined in Section 2.

Case	Criterion	Standard Wail distance (m)	Standard Two-tones distance (m)	Optimised Two-tones distance (m)
Ring Road	C1	7	13	21
	C4	24	38	34
Music comfortable	C1	9	7	9
	C4	18	19	18
Music high	C1	3	3	2
	C4	5	5	5
HT 95% 60 years	C1	3	2	4
	C4	6	8	12

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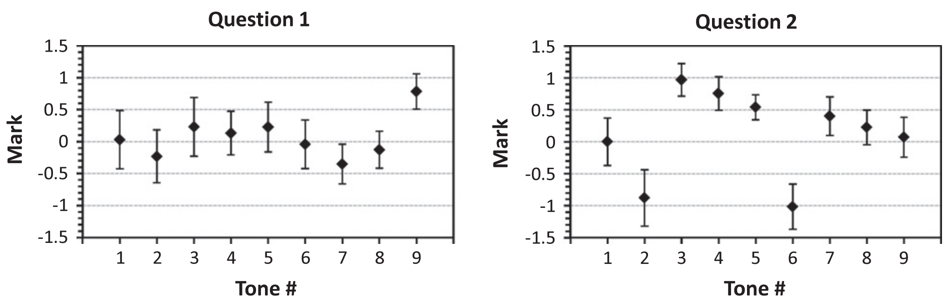

Fig. 5. Jury test marks on annoyance and urgency degree for each siren tone.

reduction of the output power increases the probabilities of not hearing the siren from a proper distance.

3.2. Annoyance assessment

The annoyance and urgency degree of the standard and new tones have been evaluated by means of a jury test. The jury was composed by 25 people otologically normal (15 male and 10 female) between 21 and 66 years old. Eight members were under 25 years old, 6 between 25 and 35 years old, 5 between 35 and 45 years old and 6 over 45 years old. In the semantic differential test, each member of the jury had to mark two questions against two opposite options after hearing a tone. The tones were played in different order for each person. The two questions were:

1. Do you consider the sound to be: Not annoying at all/very annoying.
2. Does the tone conveys: Low urgency/high urgency.

The listener had to put a tick on a line scale from −3 to 3 for each question. For each jury member their scores were normalised as to have zero mean and unit standard deviation. This is done in order to reduce the subject bias, that is the tendency of each person to use only one part of the scale and cluster its marks around it [31–33].

The test began with a training comprised of the Standard Yelp and the Two-tones of the Barcelona Police that were played again during the test because the training marks were rejected. The power output of the siren's amplifier was reduced to a level that could be tolerated during the approximately ten minute test (SPL was 75 dB at the listener's position).

The annoyance of all the tones is the same within the 95% confidence interval shown in Fig. 5 except for the New Two-tones. The 1000 Hz fundamental tone makes it more annoying. So the use of the New Wail, New Yelp and the Optimised Two-tones would improve the detectability of the siren without provoking more annoyance or reducing the urgency sensation. On the contrary, the New Two-tones is more annoying than its standard counterpart. So its use, although improving the detectability respect the standard tones, would introduce more annoyance to the citizens.

When looking at the urgency, the New Wail is perceived with significantly less urgency than the Standard Wail but at the same level of the Standard Two-tones slow. On the other hand, the New Yelp is perceived with the same level of urgency as the Standard Yelp, and the Optimised Two-tones is perceived with the same level of urgency as the Standard Two-tones fast and the Two-tones of the Barcelona Police.

4. Conclusions

The present study aims at reducing the annoyance to citizens produced by the sirens in emergency vehicles by refining their power and spectrum without compromising safety.

The power and frequency requirements have been investigated following four different detectability criteria.

In order to compute the detectability distance the following quantities have been determined: the interior background noise and noise reduction for ten different cars, the hearing threshold in quiet for different ages and nine siren spectra. Finally, the annoyance of the siren tones has been assessed by a jury test.

The main conclusion is that reducing the siren's power might create a safety problem, since there are always situations in which it is not possible to detect the siren from a fair distance (e.g. when the interior background noise is high due to the radio, or when there are people involved with hearing loss due to age). However, it is possible to increase the detectability of a siren, without increasing neither its power nor the annoyance of the warning signal, by changing the frequencies at which the sirens emit.

In this sense, two new two-tones have been proposed in this study that allow either to increase the detectability distance by 40%, with respect to other two-tones already in use with the same SPL, or to reduce the SPL by 3 dB while keeping the detectability distance and consequently maintaining the same safety level as the tones already in use.

The jury test shows that the New Two-tones (400–1000 Hz) increase the annoyance created by the siren. On the other hand, the Optimised Two-tones (390–590 Hz) is not more annoying than the tones already in use and at the same time it conveys a level of urgency compatible with the levels from other two-tones and even yelp tones.

The next step in the collaboration with Federal Signal VAMA and the Barcelona City Council is to field-test the Optimised Two-tones.

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